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Landau Damping of Electron Plasma Waves in the Linear and Trapping Regimes

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Abstract.
Linear Landau damping and nonlinear wave-particle trapping oscillations are observed with $m_\theta = 0$ standing plasma waves (Trivelpiece-Gould modes) in a trapped pure electron plasma. The measured linear damping rate ($10^{-3} \lesssim \gamma/\omega \lesssim 10^{-1}$) agrees quantitatively with Landau damping theory for moderate plasma temperatures ($1 < T < 3$ eV), and exceedingly low wave amplitudes ($\delta n/n < 10^{-6}$). At larger amplitudes, the wave initially damps at the Landau rate, then develops trapping oscillations at frequency ω_{tr}, causing the effective damping rate to decrease with amplitude as first predicted by O'Neil in 1965. For comparison, the measured damping rate is observed to decrease dramatically when the resonant particles are eliminated by truncating the nominally Maxwellian velocity distribution.

INTRODUCTION

The first experiments demonstrating linear Landau damping [1] were reported over 30 years ago by measuring the spatial damping length (k_i) of Trivelpiece-Gould (T-G) waves in an open-ended neutral plasma column [2, 3]. T-G waves are longitudinal electrostatic plasma oscillations (Langmuir waves), modified by the cylindrical boundary [4]. Landau damping occurs when resonant electrons absorb energy from the wave; these electrons have axial velocity $v_z = v_{\mathrm{ph}}$, where v_{ph} is the wave phase velocity. Nonlinear trapping oscillations were also measured in these plasmas [5, 6]. These oscillations in the wave amplitude occur when the resonant electrons become trapped and oscillate in the wave potential. Other nonlinear effects such as plasma wave echoes [7] and sideband frequency generation [8] were also observed. Even with this long history, the nonlinear regime of Landau damping and the long time behavior of Landau damped waves continues to be a subject of investigation [9, 10].

Pure electron plasmas exhibit the same plasma wave-particle resonance phenomena, since the neutral plasma ions do not participate in the dynamics [12]. Trivelpiece-Gould waves are also found in non-neutral plasmas contained in cylindrical Penning-Malmberg traps. For example, the torque from the "rotating wall" perturbations used for steady state confinement of electron [13] and positron plasmas [14] has been shown to be due to the excitation of asymmetric ($m_\theta = 1$ or 2) T-G modes. Further, the spectrum of thermally-excited $m_\theta = 0$ T-G modes has been measured in an electron plasma near thermal equilibrium [15].

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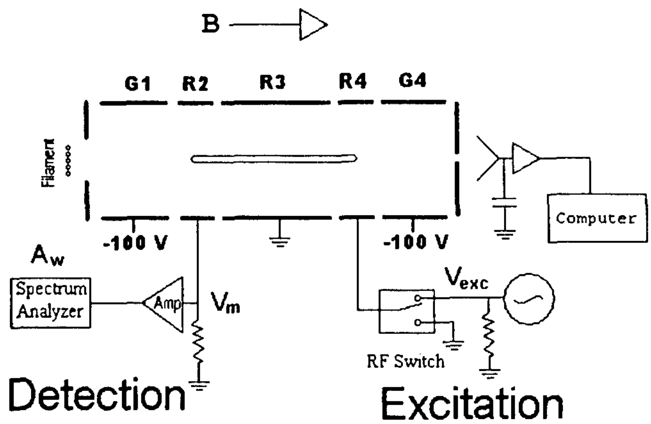

FIGURE 1. Schematic of EV Penning-Malmberg trap.

In this letter, we describe measurements of linear and nonlinear damping of standing $m_\theta = 0$ T-G waves in a pure electron plasma. The dispersion relation for these long wavelength modes is dominated by the finite radial size, with phase velocity approximately independent of mode frequency; and this frequency regime has not been previously studied. In the small amplitude regime, the measured temporal damping rates ($\omega_i \equiv -\gamma$) show quantitative agreement with the predictions of linear Landau damping. Experiments also show that larger amplitude waves exhibit trapping oscillations; and that these oscillations decrease the wave damping, as first predicted by O'Neil [16]. When the resonant particles are eliminated experimentally by truncating the nominally Maxwellian velocity distribution, the measured damping rates decrease dramatically [3].

APPARATUS

Two different Penning-Malmberg electron traps were used, both represented schematically by Fig. 1. The two principle differences between the traps are magnetic field strength and typical plasma radius. The IV machine has a superconducting solenoid, giving an axial field of 30 kGauss; whereas the EV machine has a water-cooled solenoid with an axial field of 380 Gauss. In both traps, electrons from a tungsten filament are confined in a series of conducting cylinders in a ultrahigh vacuum with background pressure $P < 10^{-10}$ Torr.

The IV machine has a wall radius of $R_w = 2.86$ cm, with a plasma radius of $R_p \approx 0.2$ cm and plasma length $L_p \approx 41$ cm (aspect ratio $L_p/R_p \approx 200$). The EV machine has $R_w = 3.51$ cm, with $R_p \approx 1.0$ cm and $L_p \approx 24$ cm (aspect ratio ≈ 24).

The traps are operated in an inject-hold-dump cycle. Both machines trap approximately 10^9 electrons total; with a central density $n_0 \approx 10^7 \text{cm}^{-3}$ for EV, and $n_0 \approx 2 \times 10^8 \text{cm}^{-3}$ for IV. The electron source for IV is in the fringing magnetic field, so the electrons are compressed to a smaller radius and correspondingly a higher density. The plasma density is measured by dumping the plasma through a movable hole onto a

Faraday cup.

The EV machine uses a magnetic "beach analyzer" for measurement of the perpendicular plasma temperature [17]. The parallel temperature is measured on IV and EV by slowly ramping the dump gate voltage while measuring the collected charge as a function of confinement voltage. The escaping charge is fit to the exponential tail of a Maxwellian to give an estimate that is accurate to about 10% for temperatures $T \gtrsim 0.2$ eV [18]. The relatively rapid perp-to-parallel thermal equilibration rate [19, 17] ($\nu_{\perp\parallel} \approx 10^3$ sec^{-1} for IV and $\nu_{\perp\parallel} \approx 10^2$ sec^{-1} for EV) allows these experiments to be described by a single temperature $[T_\perp = T_\parallel = T(r)]$. Furthermore, the radial temperature variations are small enough to be ignored here.

The T-G modes are excited by a short burst (10 cycles) at the wave resonant frequency (ω_0) applied to cylinder R4. The resulting wave density fluctuations induce image charges on cylinder R2, and these are detected using either a low-noise current amplifier or a low-noise 50-ohm RF amplifier. The received signal is filtered and fed into a RF spectrum analyzer tuned to the resonant frequency with a bandwidth of 300 kHz. A separate signal generator is usually attached to cylinder R3 to provide controlled heating of the plasma [20]. The heating frequency is set close to the thermal bounce frequency ($\bar{f}_b = \bar{v}/2L_p$), which is less than $1/3\ \omega_0$, assuring no coupling to the T-G mode.

For these experiments we launch the $m_z = 1$, $m_r = 1$ T-G mode, also known as the "sloshing" mode. This is the lowest order longitudinal oscillation of the plasma column, and has the nodes of the axial electric field (E_z) at the ends. This means that the wavelength λ is approximately twice L_p, with wavenumber $k_z = 2\pi/\lambda \approx \pi/L_p$. Numerical simulations have shown that the finite length of the plasma column acts to slightly increase the effective wavelength [21]. thus making the effective wavenumber k_z^{eff} slightly smaller than π/L_p. Numerical solutions of the drift-kinetic equations for an infinite-length column with $n(r)$ and $T(r)$ determine a wavenumber k_z^∞ which gives the observed mode frequency ω. We presume that the finite-length column has $k_z^{\text{eff}} = k_z^\infty$, and calculate the wave velocity as $v_{\text{ph}} = \omega/k_z^{\text{eff}}$.

THEORY

Landau was the first to describe the resonant interaction of electrostatic waves with particles traveling at the wave phase velocity, v_{ph} [1]. Depending on the slope of the particle velocity distribution at v_{ph}, this resonant interaction can cause either wave damping or wave growth. For Langmuir waves in an infinite homogeneous plasma with a Maxwellian velocity distribution, Landau calculated a damping γ_{LD} given by

$$\frac{\gamma_{\text{LD}}}{\omega} \approx \sqrt{\frac{\pi}{8}} \left(\frac{v_{\text{ph}}}{\bar{v}}\right)^3 \exp\left[-\frac{1}{2}\left(\frac{v_{\text{ph}}}{\bar{v}}\right)^2\right], \tag{1}$$

with $v_{\text{ph}} = \omega/k_z^{\text{eff}}$ and $\bar{v} \equiv \sqrt{T/m}$. This equation comes from an approximate expansion of the Zeta function to lowest order in the parameter $\bar{v}/v_{\text{ph}}$ [22]. In the early experiments by Malmberg *et al.* [2], a similar expression for k_i/k_r was tested by varying the wave phase velocity and measuring the corresponding spatial damping length k_i using a

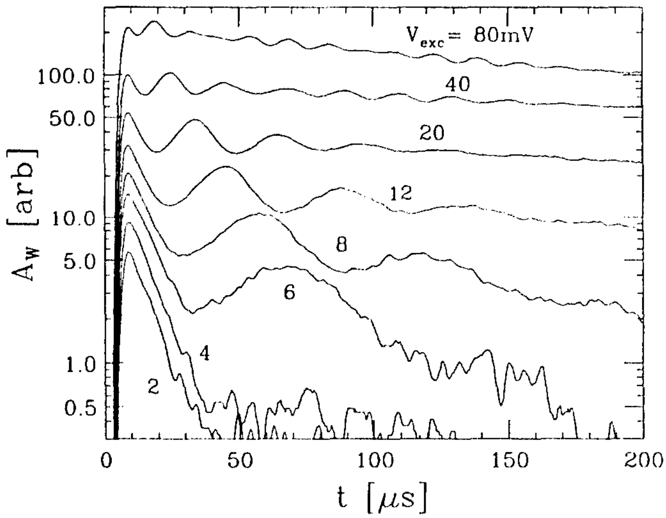

FIGURE 2. Decay of received amplitude versus time for various excitation amplitudes (V_{exc}). The waves were excited by a 10 cycle burst at 3.2 MHz ($\bar{v}^2/v_{ph}^2 = .08$).

plasma at a fixed temperature. For our experiments, the mode frequency is approximately

$$\omega \approx \left(\frac{k_z^{\text{eff}}}{k_\perp}\right)\omega_p\left[1+\frac{3}{2}\left(\frac{\bar{v}}{v_{ph}}\right)^2\right], \tag{2}$$

where $1/k_\perp \approx R_p\sqrt{\frac{1}{2}\ln(R_w/R_p)}$ and $\omega_p = \sqrt{4\pi ne^2/m}$, so the phase velocity is relatively insensitive to any change in frequency. In order to vary the damping rate we heat the plasma. This changes $\bar{v}$ at roughly constant v_{ph}, enabling a comparison to Eq. (1). The slight temperature dependence of the phase velocity is accounted for in the estimates of $\bar{v}/v_{ph}$.

RESULTS

Figure 2 shows a logarithmic plot of the received wave amplitude versus time for different excitation amplitudes (V_{exc}). Three observations can be made: First, the peak of the received wave amplitude A_w depends linearly on the amplitude V_{exc} of the drive, as expected for linear waves. Second, for low amplitudes ($V_{exc} < 4$ mV), the wave damps exponentially, at a rate independent of amplitude; this is the regime of linear Landau damping. Third, as V_{exc} is increased above 8 mV, we observe the appearance of nonlinear temporal oscillations that inhibit the damping of the wave. At larger amplitudes ($V_{exc} \gtrsim$ 20 mV), we observe that after the fast initial damping the wave exhibits oscillations with very little average amplitude decay.

From the data in Figure 2, we define three quantities for comparison to theory. First, the initial damping of the wave is defined to be γ_{lin}. Second, the (slower) average decay

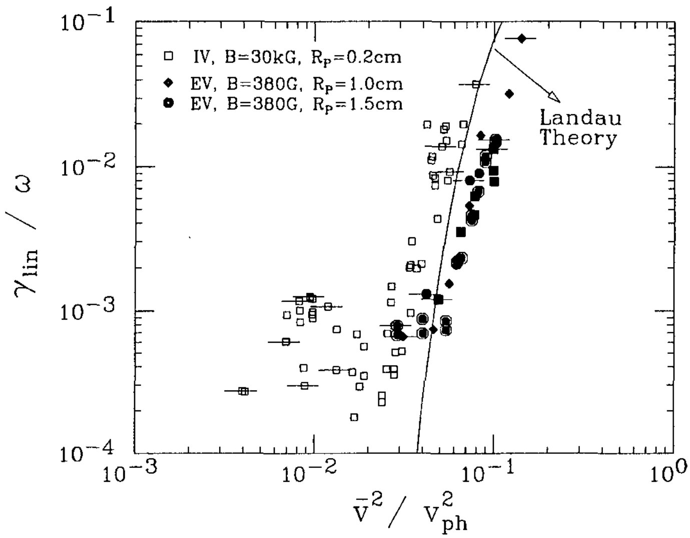

FIGURE 3. Measured linear damping rate compared to prediction of Landau.

rate of the wave over 200 μs is defined to be γ_{avg}. Third, we define a trapping frequency ω_{tr} by measuring the time Δt between the peak of the excitation and the peak of the first oscillation, with $\omega_{tr} \equiv 2\pi/\Delta t$.

Data sets similar to Figure 2 were taken over a range of plasma temperatures, thereby varying the value of $\bar{v}/v_{ph}$. Figure 3 is a plot of the initial damping γ_{lin} versus $\bar{v}^2/v_{ph}^2$, along with the Landau prediction from Eq. (1). For high temperatures, the data agrees with the linear theory of Landau over 2 decades in damping, an apparent 50% uncertainty in $\bar{v}^2/v_{ph}^2$. At lower temperatures, where Landau damping is expected to be small, we observe a damping "floor" of $10^{-3} - 10^{-4}$ which is likely caused by resistive dissipation in the measurement circuit [15].

The nonlinear effects are summarized in Figure 4, where the normalized average damping rate $\gamma_{avg}/\gamma_{lin}$ and the normalized trapping frequency ω_{tr}/γ_{lin} are plotted versus wave excitation amplitude V_{exc}. Also plotted is a dashed line showing the expected scaling of $\omega_{tr} \propto V_{exc}^{1/2}$. The trapping frequency shows good agreement with the expected scaling at high amplitudes, but shows a small systematic deviation at the lowest excitation amplitudes. This deviation is expected because for wave amplitudes such that $\omega_{tr}/\gamma_{lin} \sim 1$ there is significant damping before the first trapped particles can execute a complete trapping oscillation, leading to an effective trapping field that is slightly smaller than initially. This effect has been seen in numerical self-consistent calculations of the damping rate as a function of time [23] and in experiments by Franklin [24].

The average damping rate γ_{avg} is seen in Figure 4 to drop by more than an order of magnitude from the Landau rate as ω_{tr} becomes larger than γ_{lin}. This drop is expected, since trapped particles cause a periodic re-growth of the wave. However, theory predicts the wave damping should eventually become zero, in the absence of other decay

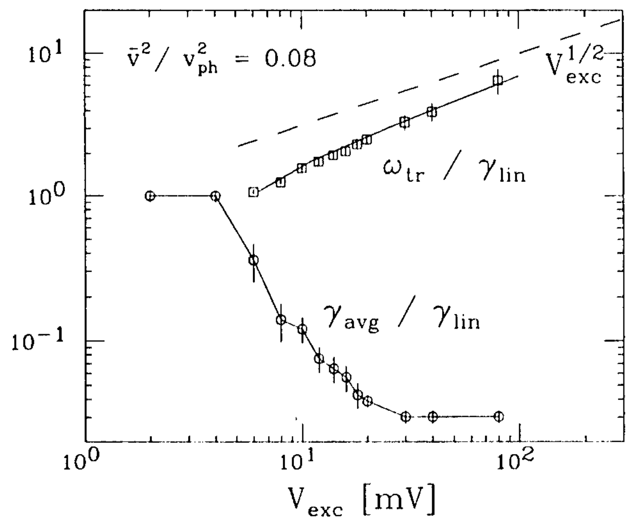

FIGURE 4. Normalized trapping frequency and normalized average decay rate versus excitation voltage. The dashed curve shows the expected scaling of trapping frequency with amplitude.

mechanisms. The experiments always measure some amount of residual damping. This residual damping, also seen clearly at low temperatures in Fig. 3, has been identified as due to resistive elements in the excitation and detection circuits [15]. In Figure 4, the small damping rate ($\gamma_{avg}/\gamma_{lin} \approx .03$) at large amplitudes corresponds to an effective real part of the external impedance of about 5 Ω [15].

We have verified that γ_{lin} is due to resonant particles at v_{ph} by experimentally truncating the particle velocity distribution. When the confinement gate is ramped down, the highest energy particles are the first to escape. To measure damping on a truncated distribution, the plasma is first prepared by ejecting the high energy particles, then the wave is excited and the damping rate measured. It was observed that if the electrons with $v_z \gtrsim v_{ph}$ were ejected over most of the plasma radius, then the fast initial damping does not occur; the wave only damps at the residual resistive-damping rate. This qualitatively shows the sensitivity of the damping rate on the details of the tail of the velocity distribution, as would be expected for Landau damping.

CONCLUSIONS

At very small wave amplitudes, linear Landau damping is observed over the range $10^{-3} < \gamma_{lin}/\omega < 10^{-1}$. There appears to be some systematic shift between the two different apparatuses used. This is most likely due to the different geometry, namely the plasma aspect ratio (R_p/L_p), and the closeness of the plasma to the wall (R_p/R_w). For instance, the overlap of the mode potential and the plasma density shows substantial radial dependence. These profile effects could easily lead to errors in the estimated phase velocity and thus lead to a systematic error in applying the theory.

From the measured received wall voltage we can calculate the magnitude of E_z for the launched T-G mode. This value for E_z gives an expected trapping frequency ($\omega_{tr} \equiv \sqrt{ek_zE_z/m}$) that differs from the measured value by a factor of 3. However, uncertainties in the detector calibration and theoretical predictions have made it difficult to make an absolute comparison.

Unlike the early experiments [5, 6], the spectrum of T-G modes is discrete at these long wavelengths. This means we do not expect to have any sideband instability develop, and experimentally none have been observed. This unique characteristic should allow future experiments to contribute to the debate over the long time behavior of Landau damped waves [9, 25, 26].

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